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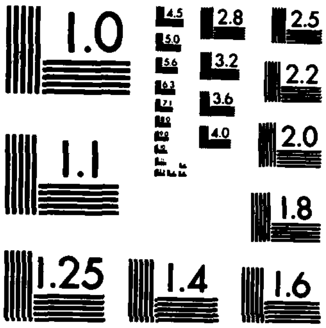

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OBSERVATIONAL-NUMERICAL STUDY OF MARITIME EXTRATROPICAL CYCLONES USING FGGE DATA

Russell L. Elsberry
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May 1985

Final Report for Period June 1982 - May 1985

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Prepared for: National Aeronautics and Space Administration
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Analysis of First GARP Global Experiment (FGGE) data by the European Centre for Medium-range Weather Forecasts and the Goddard Laboratory for Atmospheric Sciences have been used to study three cases of maritime extratropical cyclone development. It has been demonstrated that these FGGE analyses are consistent with the observations through synoptic comparisons and satellite interpretations. Quasi-Lagrangian diagnostic budgets of mass, vorticity, angular momentum and heat have been computed in pressure coordinates for observed and model-generated cyclones. The roles of jet streaks and small static stability in the lower

troposphere during rapid development of maritime cyclones have been documented. Vertical circulation trends in the mass budget are consistent with the sea-level pressure evolution in each case. Inward transport of vorticity due to the jet streak coincides with the rapid development phase. Vorticity budgets of these maritime cyclones appear to be consistent with earlier studies of continental cyclones.

To complement the observational studies, similar diagnostic studies have been done for numerical simulations of maritime cyclogenesis under straight upper-level flow. These studies demonstrate that similar physical mechanisms are involved in the simulated storms as were found in the FGGE-based studies.

Two sets of numerical model predictions from the FGGE analyses were examined for an explosively deepening cyclone over the western North Pacific Ocean. Both ~~the~~ GLAS and the UCLA models predicted the most rapid deepening phase too early and resulted in too low sea-level pressures. For this case, the NOSAT analysis (excluding all satellite data) resulted in a more accurate prediction of the track and sea-level pressure evolution. This result is due to an incorrect specification of the satellite cloud-drift winds in the region of the jet stream. Heat budget studies indicate that the heating rates in this maritime cyclone are very much larger than in continental cyclones. The sea-level pressure changes in the maritime cyclone predictions appear to be highly correlated with the magnitude of the heating rate. A semi-prognostic technique for inferring the diabatic process from the FGGE analyses has been developed. An inter-comparison study with numerical model output showed similar maximum heating rates as deduced from the semi-prognostic technique.

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1. Introduction

Significant new sources of meteorological data became available over the oceanic regions from the First GARP Global Experiment (FGGE) during 1979. FGGE represented an unprecedented international effort at observing weather patterns with a wide variety of relatively new observational systems, with emphasis on data-sparse regions. Advanced satellite-derived soundings, satellite cloud-drift winds, commercial jet wind observations, ocean buoys and reconnaissance flights with dropsondes were utilized to expand significantly meteorological data bases in data-sparse regions. The FGGE data that are especially valuable for the study of the maritime extratropical cyclones include the satellite cloud winds and the infrared and microwave sounder data over the oceans.

The FGGE data have been combined into dynamically consistent analyses at the European Centre for Medium-range Weather Forecasting (ECMWF) and at the Goddard Laboratory for Atmospheric Sciences (GLAS). Personnel at GLAS also prepared a high-quality, edited Level II-B data base that can be used to evaluate the objective analyses.

The objective of this research has been to use these FGGE analyses to better understand the development, maturation and decay of maritime extratropical cyclones. A combined observational and numerical approach has been utilized. A quasi-Lagrangian diagnostic approach developed originally at the University of Wisconsin has been used for studying three cases of maritime extratropical cyclones. Budgets of mass, velocity, angular momentum and heat have been computed in pressure coordinates for observed and model-generated cyclones. The diagnostic results from the FGGE analyses will be described in the next section. Diagnostic studies of the output from an early version of the Navy Operational Global Atmospheric Prediction System will be discussed in the third section. Finally, the results from two sets of predictions from FGGE analyses will be described.

2. Diagnostic Studies Based on FGGE Analyses

Three case studies of explosive cyclogenesis during FGGE SOP-1 were completed under the project. The first case to be reviewed is a large-scale system which developed over t e western North Pacific Ocean during 12-16 January 1979. The second case is a polar-type cyclogenesis that formed south of Iceland during 26-27 January 1979. These cases were selected because of the following features:

(1) relatively good surface (ship) and upper-level (satellite and aircraft) data coverage;

(2) explosive development; and

(3) straight flow aloft (500 mb), which suggests minimal upper-level support for cyclogenesis as in the type A category of Petterssen and Smebye (1971).

The final case was the Presidents' Day cyclone of 18-20 February 1979, which was an intense subsynoptic coastal development. Both budget and diagnostic trajectory studies (in collaboration with scientists at Goddard Laboratory for Atmospheres) were completed on this cyclone.

a. Western North Pacific Cyclone. This cyclone develops explosively southeast of Japan on 13 January 1979 and transits rapidly northeastward (40-50 knots) toward a final position off the Alaskan west coast on 16 January. The cyclone deepens from 1010 to 947 mb during this period. This system develops rapidly on a strong frontal zone under fairly straight flow aloft. However, an intense jet streak at 250-200 mb triggers the development and the incipient low explosively deepens as it moves under the divergent left-front quadrant of the jet. Satellite images document extensive convective activity during the cyclogenesis and reveal a number of interesting

mesoscale cloud structures, such as convective lines in the southern quadrant, multiple frontal bands and rope cloud structure. The cyclone showed a deceptive lack of large-scale organization even though the central sea-level pressure was less than 980 mb in the early development period.

The synoptic investigation indicates the ECMWF analyses provide a good representation of the 3-dimensional structure of this western North Pacific cyclone. The objective analyses are consistent with DMSP imagery and other data, and resolve the rapid development as well as the NMC manual analysis, which is the standard of comparison. Therefore, the enhanced data sources during the FGGE SOP and the ECMWF data assimilation system provide a representation of this maritime extratropical cyclone that is adequate for diagnostic studies.

The quasi-Langrangian mass and vorticity budget analyses were computed using the ECMWF FGGE Level III-b analyses to explore this open-ocean cyclogenesis case. The low tropospheric (1000-500 mb) static stability within the local environment of the cyclone decreases dramatically during the formative and early explosive cyclogenesis periods. This destabilization creates a favorable environment for the early outbreak of vigorous convection and large-scale upward vertical motion near the storm center.

The lateral mass circulation for 6^0 radius shows a temporally-consistent two layer pattern with maximum inflow (surface convergence) in the lowest layers (1000-700 mb) and strong upper-level divergence. The mass circulation is most intense during the explosive cyclogenesis period. The level of non-divergence for the 6^0 and larger volumes rises during the explosive development as the convergent inflow layer thickens.

Storm-scale vertical motions in isobaric coordinates derived from the ECMWF initialized fields, kinematically from analyzed winds, and from the mass

budget are compared. The kinematic and mass budget areal average omegas are similar and show an intense storm-averaged upward maximum of greater than -3 μb/s during the rapid development. The vertical motion averages from the ECMWF initialized fields are only 50-70% of the kinematic values. The vertical motion maximum is initially at 700 mb and rises to 500 mb during the later periods as the vortex grows vertically.

The vorticity diagnostics show the horizontal advection of vorticity is an important term even though the cyclone develops without a significant short wave trough aloft. An intense maximum centered near 225 mb develops after 00 GMT 13 January. This feature represents the advection of cyclonic shear vorticity into the cyclone volume by the strong jet streak aloft. This source of vorticity coincides with the strengthening of the cyclone mass circulation and the explosive development phase. Large negative values of horizontal advection are found in the low troposphere due to the inward mass flux, the rapid storm motion and the anticyclone ahead of the developing system.

The divergence term of the vorticity budget is a strong vorticity source in the low troposphere due to the intense convergence and, although partially offset by friction, is the primary factor in the low-level spinup. The inward positive vorticity advection aloft, first associated with the jet maximum and later due to self-development, is greater than the vorticity sink associated with divergence aloft and accounts for upper-level development during the occlusion stage. The vertical advection and tilting terms offset each other in the same manner as discussed by DiMego and Bosart (1982b).

The residual term of the budget contains the effects of the omitted processes plus the accumulated errors in the calculation of the resolved terms. The residual is positive (apparent vorticity source) in the upper

troposphere and negative (apparent sink) in the low levels. These residuals suggest the vertical motions may still be too weak, or that mesoscal- vertical transfers due to convection are not properly represented in the budget in agreement with the cyclone study of Chen and Bosart (1979) and tropical wave studies of Reed and Johnson (1974).

The above results were obtained using ECMWF analyses at 00 and 12 GMT. During the 48-h period the system was not observed by radiosondes (00 GMT Jan 13 to 00 GMT Jan 15), these analyses were in agreement with satellite observations and produced useful diagnostics. One exception is the mid-tropospheric analyses of 00 GMT Jan 14 in which the low and mid-troposphere are too warm and the 500 mb wave is too weak in comparison to the growth rate implied during earlier and later time periods.

Additional analyses at 06 and 18 GMT are available during the First Special Observation Period of FGGE. Our initial plans were to use these analyses plus the 00-12 GMT analyses for 6-h time resolution in the diagnostics. These 6-h budget results were very noisy with large 12-h fluctuations in storm statistics from both the wind and mass field because of spurious warming near the storm center.

The mass and vorticity statistics of this open-ocean cyclone are consistent with the development of extratropical cyclones over land as described by Petterssen (1955) and Palmen and Newton (1969) and the recent case studies of Chen and Bosart (1979) and DiMego and Bosart (1982b). What is remarkable is the intensity of the explosive cyclone development and the magnitudes of the budget terms. Although the case was selected because of its apparent similarity to the Petterssen et al. (1962) and Petterssen and Smebye (1971) type A development based on the 500 mb and surface patterns, the

detailed studies show that this cyclone does not fit the Petterssen category. Appreciable upper level support is found in this case with an intense jet streak which triggers the explosive development.

These results suggest upper-level forcing may play a greater role in the initiation of explosive oceanic development than the Petterssen description suggests. Also, additional evidence is presented on the importance of planetary boundary layer processes and convective processes in explosive development as suggested by Sanders and Gyakum (1980).

b. North Atlantic Polar Low Development. The second observed FGGE cyclone case develops rapidly south of Iceland on 26 January 1979. This system deepens from 1010 mb to 978 mb over a 36-h period as it moves southeastward toward the British Isles.

The synoptic and diagnostic investigation of this case reveals similar results to the North Pacific system. The incipient cyclone develops within a strong low tropospheric baroclinic zone; however, little mid-level short wave activity is observed. The rapid development coincides with movement of the divergent left front quadrant of a polar jet streak into the budget volume. The vertical stability of the cyclone is quite low (approaching moist adiabatic) in agreement with Mullen's (1979) analysis of Pacific polar low systems.

The mass and vorticity diagnostics capture the vigorous growth of the cyclone circulation and agree well with the surface pressure analyses and satellite interpretations. Even though the horizontal scale of the polar low is smaller, the budget statistics generally follow the results of Wash and Calland (1985). The upper-level inward advection of vorticity at the jet level (300 mb) coincides with the development of the cyclone mass

circulation and the rapid creation of low-level vorticity. Problems with the 06 and 18 GMT analyses also were isolated in this case.

c. Presidents' Day Cyclone. The Presidents' Day cyclone of 18-20 February 1979 was an intense and rapidly developing storm which produced heavy snowfall along the east coast of the United States. Research on this cyclone was directed toward conducting diagnostic storm-centered budget studies and studying jet streak interaction with this cyclone. The budget studies are described in an NPS M.S. thesis by Conant (1982). The jet streak studies (Uccellini *et al*, 1984, 1985) were completed in collaboration with scientists at the Goddard Laboratory for Atmospheres.

Conant (1982) used ECMWF analyses to evaluate absolute vorticity and storm angular momentum budgets. The budget statistics of this cyclone also illustrate the importance of the polar jet streak and amplifying mid-level trough in the explosive SLP development observed 00-18 GMT 19 February. The average horizontal advection of vorticity (or convergence of eddy angular momentum transport in the storm angular momentum budget) dominates the budget forcing terms and coincides with the intensification of the cyclone mass circulation, large production of vorticity by the low-level convergence and the largest SLP falls.

The jet streak studies isolated three jets that played important roles in the development of the cyclone and associated heavy precipitation. Initial studies focused on the subtropical jet stream (STJ)(Uccellini *et al*, 1984). Diagnostic investigation reveals increasingly unbalanced flow in the STJ with super-geostrophic flow greater than 30 ms^{-1}. The upper-level divergence associated with the STJ was linked to the intensification of the

low-level jet along the east coast. This low-level jet played a key role in transporting moisture into the heavy precipitation areas in the incipient cyclone.

Subsequent studies (Uccellini _et al_., 1985) focused on the amplifying polar jet which played a major role in the cyclone budget results. This study illustrated the role of dynamically forced mesoscale vertical circulations on the deformation of the tropopause and extrusion of stratospheric air along the axis of the polar jet. The dramatic tropopause fold which occurred during the trough amplification is consistent with subsidence that would be expected from geostrophic deformation patterns associated with the jet streak. This folding process extruded dry stratospheric air with high values of potential vorticity down toward the 700 mb level at a location 1500 km upstream of the east coast between 12 to 24 h prior to the explosive development phase of the cyclone. NIMBUS-7 water vapor and ozone measurements suggest the stratospheric air mass was nearly co-located with the cyclone center as explosive deepening and vortex development occurred.

3. Diagnostic Studies with Model-generated Data

The diagnostic studies with FGGE data described above are the primary results of this research project. Complementary studies with model-generated data were also completed as a guide to the interpretation of the observational cases. There are several advantages in using the model-generated data. First, a complete and accurate specification of the fields and physical processes in the model is available, which cannot be achieved in an observational study. An early study by Tallman (1982) of the mass budget in the numerically-simulated cyclone from Sandgathe (1981) was useful as a consistency check of the QLD budget algorithm. In our recent studies (Bosse, 1984; Liou and Elsberry, 1985; Winninghoff and Elsberry, 1983), the role of diabatic processes in the energetics of the model storm could be illustrated.

A second advantage of the 3 h time resolution from model history tapes is that rapid changes can be resolved with confidence. Many of the maritime systems studied by Sinclair (1984) and Sinclair and Elsberry (1985) are relatively short-lived, and can only be studied with the 3 h model-generated data. One of the disappointments in the FGGE analyses available thus far is the inaccurate thermal analyses at 06 and 18 GMT (Wash and Calland, 1985; Wash and Elsberry, 1984). Time derivatives in the observational studies then must be taken over 12-h intervals rather than 6 h.

The third advantage of model-generated fields is that the horizontal and vertical variations are dynamically consistent. In the observational studies, there may be horizontal differences due to data inhomogeneities between land and ocean regions. Likewise, vertical differences may be generated by incorrect assimilation of different data types. It is important to counterbalance these statements by emphasizing that the dynamical solutions represented by the model fields are contaminated by deficiencies in numerical solution techniques. Furthermore, the model parameterizations of the physical

processes are also incomplete. Thus, we advocate the study of model-generated data only as a complement to observationally-based budget studies.

A final advantage of the model-generated data is that the complete evolution of the cyclone is known. This complete record is particularly valuable in tracing the early stages of the maritime perturbations studied by Sinclair and Elsberry (1985). Some polar lows appear to result from a pre-existing low-level perturbation that is actually the remnant of a prior cyclone that has rotated around the parent cyclone, whereas other lows are associated with a mid-tropospheric short wave. These origins can not always be traced with observational data because data deficiencies over the polar ocean and in the mid-troposphere often prevent a clear distinction. With complete 3 h coverage in the model-generated data, Sinclair and Elsberry (1985) were able to document completely both types of cases.

a. <u>Case study of cyclogenesis under anticyclonic upper flow.</u> Sinclair and Elsberry (1985) describe a case from the Sandgathe (1981) simulation that appeared to be very similar to the polar low case studied by Cook (1983) and Wash and Cook (1985) based on FGGE data. In both cases, a relatively small disturbance intensifies within the northwesterly flow behind a major cyclone. The disturbances expand horizontally as they develop, and eventually become the primary centers. As in the Cook (1983) case, the initial development in the simulation was within a highly baroclinic thermal ridge. Although the mid-tropospheric flow was anticyclonic, an upper-level jet streak seemed to play an important role in both cases. In Cook's case, the disturbance developed under the left exit quadrant, whereas the disturbance in the model data was under the right rear quadrant. Thermal advection appeared to play a key role in the development, and latent heat release within the warm air also contributed to self-amplification. By the end of the development, the system

was in a region of reduced low-level baroclinity. These synoptic features are similar to the Petterssen et al.(1962) and Petterssen and Smebye (1971) Type A developments. A major objective of the Sinclair and Elsberry study was to determine if quantitative measures of the Type A development could be gained from budgets of the model-generated data.

The mass budgets from numerical model simulations should be highly accurate since the mass continuity equation is an integral feature of the solution procedure. Tallman (1982) documented a 12-h oscillation that was superposed on the synoptic deepening trend. Sinclair and Elsberry (1985) found wave number one meridional waves caused a "sloshing" effect in the model fields. Furthermore, the instantaneous fields of vertical motion in sigma coordinates contain high frequency components related to external gravity waves. It was thus necessary to horizontally smooth the predicted fields to minimize the effects of these high-frequency waves. After this smoothing is applied, the trend in the diagnosed mass circulation is consistent with the development of the polar low. Vertical growth in the depth of the convergent lower layer is quite realistic, with a rise of the level of non-divergence from 750 mb to 490 mb near the end of the development.

The vorticity budget from the model-generated data was closed to an acceptably small residual. Low-level vorticity is generated by the increasing mass circulation and is lost to friction (part of the residual term), horizontal eddy fluxes and vertical export. The growth of surface vorticity due to low-level convergence has been found in other QLD budget studies (Chen and Bosart, 1979; DiMego and Bosart, 1982b; Calland, 1983; Cook, 1983; and Bosart and Lin, 1984).

Upper-level vorticity increases in the model simulation are related to the rapid development of the upper-level ridge/trough system via the self-amplifi-

cation process. The upper-level ridging above the region of low-level warm advection and precipitation was more dramatic in the model data than in the FGGE data used by Cook (1983). Thus, the increase in positive vorticity was delayed in the model storm whereas the polar low of Cook had vorticity increases aloft as soon as the mass circulation intensified. This may indicate an excessive or overly efficient latent heat release in the simulated storm. The strongest cyclogenesis was concurrent with the most rapid increase in upper-level positive vorticity advection (PVA). The PVA increase in Cook's case was associated with the propagation of the exit region of the jet streak into the volume. In the simulated polar low, the jet streak remained poleward of the surface feature during the first 36 h, and only later in the sequence was there a (new) jet streak equatorward of the feature.

Comparison of this model-generated polar low case and that of Cook (1983) based on FGGE data illustrates the difficulty of forecasting such developments under anticyclonic upper flow. It will clearly be necessary to resolve relatively small horizontal scale features at lower levels in relation to narrow jet streaks at upper levels. In the absence of conventional data over the oceans, space-based systems must be utilized to provide the required observations.

b. Concluding remarks. Careful synoptic-type analysis and budget studies of several model-generated maritime cyclones have been carried out. The comma-shaped features appear to be similar in many respects to the observed cases of Cook (1983) and Locatelli *et al*. (1982). The role of latent heat release appears to be relatively more important for these small maritime systems. In other cases, we conclude that these small-scale features develop or do not develop for very similar reasons as do larger scale cyclones. Our model-generated data studies may be criticized in that the primary "physics"

included in the model is that appropriate for the larger scale cyclones. Nevertheless, these results suggest a hypothesis that the differences in maritime cyclones versus the more extensively studied continental cyclones is the relative strength of the convective processes in a low static stability (or low Richardson number) environment. Such a hypothesis can only be tested with more observational studies of maritime cyclogenesis.

4. Diagnostic studies with predictions from FGGE analyses

A natural extension of the above diagnostic studies is to also use a similar approach to study the predictions initiated from FGGE analyses. Rather than perform the integrations with the Navy Operational Global Atmospheric Prediction System as originally proposed, we obtained two other sets of predictions. Dr. Wayman Baker provided the forecasts from the nine-level, fourth-order, coarse-mesh (4° x 5°) Goddard Laboratory for Atmospheric Science (GLAS) model. This model was initialized with the GLAS analyses of FGGE Level III-B data from all sources (hereafter termed SAT) and from a restricted set that excluded all satellite data (NOSAT). The second set of prognoses was made with a nine-level, fourth-order, fine-mesh (2.4° x 3°) version of the University of California at Los Angeles (UCLA) model (kindly provided by Professors Arakawa and Mechoso). This model run was initialized from ECMWF analyses and included 10 days of integration.

The primary objective in these intercomparisons is to better understand the processes involved in explosive development of maritime cyclones. Thus, the focus has been on the case in the western North Pacific studied by Calland (1983) and Bosse (1984). The models have different grid resolution and use slightly different initial conditions. Therefore, the intention is not to evaluate the relative merits of the two models, but rather to examine the differences and similarities in their forecasts as possible indicators of relevant physical processes. Detailed analyses of the cases are accomplished by mass, vorticity and heat budgets using the QLD approach.

a. <u>NOSAT versus SAT comparisons</u>. Ebersole (1984) and Peak <u>et al</u>. (1985) compare the GLAS model predictions from NOSAT and SAT initial conditions on 00 GMT 13 January 1979. It was somewhat surprising that the NOSAT prediction of the cyclone track was superior to that from the SAT analysis. Both predictions

over-deepened the low during the rapid deepening phase, in contrast to earlier studies in which the numerical predictions under-forecast cyclogenesis (e.g., Bosart, 1981; Anthes, Kuo and Gyakum, 1983). A major factor in the SAT and NOSAT cases is the position and strength of the upper-level jet streak. The weaker jet stream winds in the SAT initial conditions have been traced to invalid altitude assignments of the Japanese cloud-drift winds. The attempt by University of Wisconsin personnel to reassign the winds to a more representative level prior to the data assimilation was not completely successful. Stronger divergent components in the westerly jet led to a more intense development and a farther eastward track (and closer to actual track) in the NOSAT predictions. This sensitivity to the strength of the jet streak winds between the two analyses reinforces the conclusions from the diagnostic studies of the crucial role of jet streaks in explosive cyclogenesis.

Low-level forcing is also a prime candidate as an initial cyclogenesis mechanism. The storm developed within a large-scale flow of continental polar air around an intense Siberian high and across the warm western North Pacific. These conditions typically produce a destabilization of the boundary layer within the incipient storm region (Sandgathe, 1981). As shown in Fig. 1, the potential temperature gradient between 500 and 1000 mb in the GLAS analyses is nearly equal to that from the ECMWF analyses. The SAT and NOSAT prognoses develop a much lower static stability than was analyzed. This persistently low static stability may be attributed to greater mid-tropospheric cooling and a smaller surface cooling rate compared to the analyses. These extremely low stabilities are a major factor contributing to the development of the simulated cyclones.

A time section of area-averaged omega for the GLAS analysis (Fig. 2a) illustrates the mid-tropospheric maximum during the explosive phase of

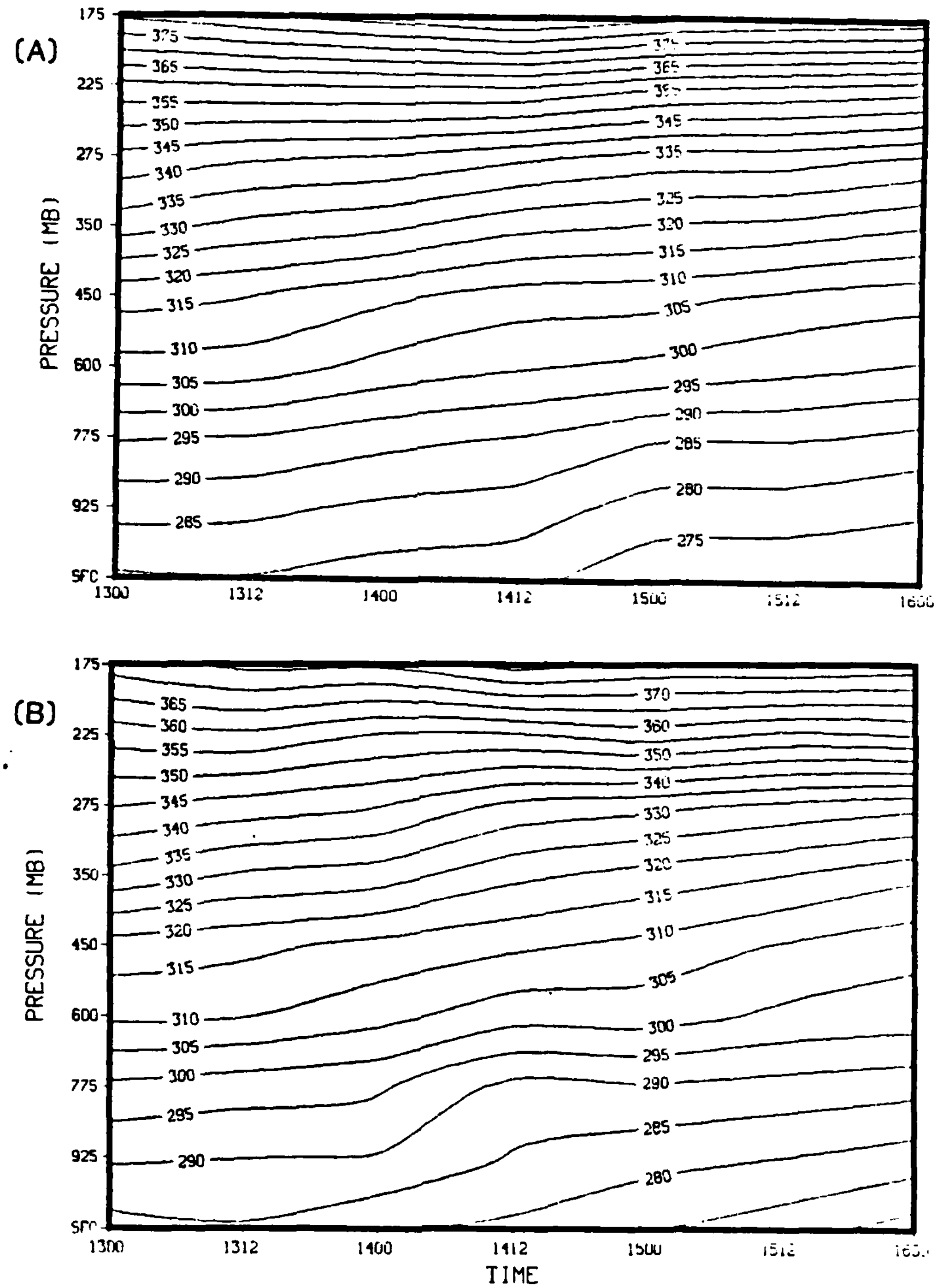


Fig. 1 Analyzed area-averaged potential temperature time sections (a) GLAS (b) ECMWF. Values are in Degrees Kelvin. Time 1300 refers to 00 GMT 13 January.

development. This vertical mass transport maximum occurs 12 h earlier in the SAT case (Fig. 2b) and has a smaller maximum. The NOSAT vertical velocities (Fig. 2c) become larger early in the forecast, which contributes to a more rapid development in this case. These differences are very likely due to the differences in the jet stream intensity in the SAT and NOSAT cases discussed above, and re-emphasize the importance of an accurate jet analysis for this maritime explosive cyclogenesis case.

The three major terms in the vorticity budget are lateral vorticity transport, vertical vorticity transport and source/sink terms. The differences in vertical velocity illustrated in Fig. 2 contribute directly to the latter two terms. The lateral transport of absolute vorticity (Fig. 3) is stronger aloft in the SAT prediction and weaker in the NOSAT prediction relative to the analysis. Viewed from a different perspective, the horizontal vorticity advection is larger in the NOSAT case than in the SAT case, but the larger horizontal divergence overcomes the advective effect, and leads to smaller total transport.

In summary, comparison of the budgets based on the SAT and NOSAT predictions relative to those from analyses indicates the sensitivity to initial conditions. Accurate low-level static stability and upper-level wind analyses appear to be essential factors in predicting maritime cyclogenesis.

b. Heat budget studies. These heat budgets were prepared for the same western North Pacific cyclogenesis case using the ECMWF analyses and the UCLA predictions (Liou and Elsberry, 1985). It is interesting that the UCLA model also over-predicted the cyclogenesis.

The diagnosed mass-averaged heating rate for the analyzed and predicted cyclones are shown in Fig. 4. Because the heating rate was computed as a residual of the temperature changes and the horizontal and vertical fluxes,

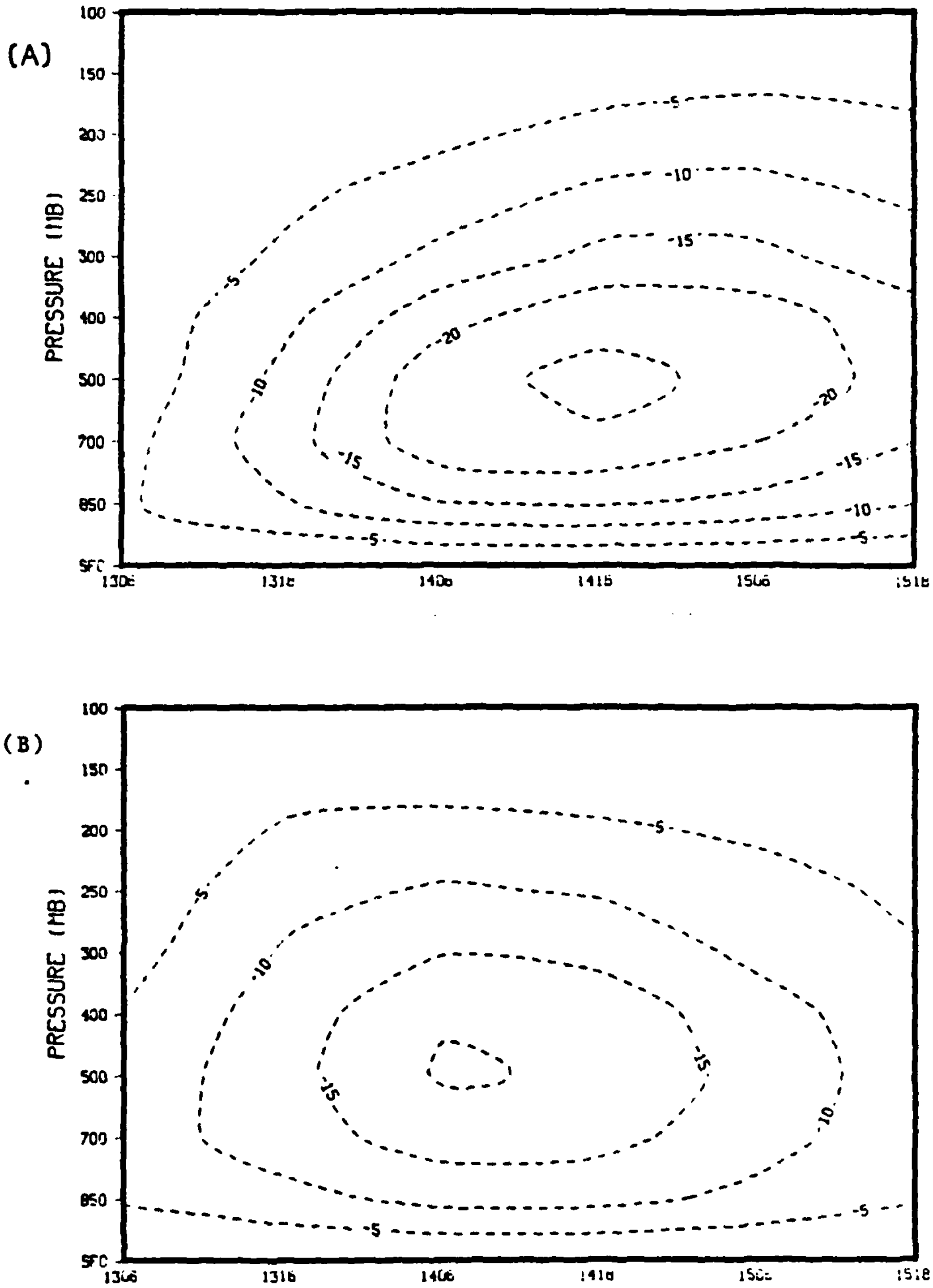


Fig. 2 Time section of area-averaged kinematic vertical velocity ((mb/sec)* 1000) for (a) GLAS analysis, (b) SAT prognosis, and (c) NOSAT prognosis. 1306 indicates 12 h time interval centered at 0600 GMT 13 January.

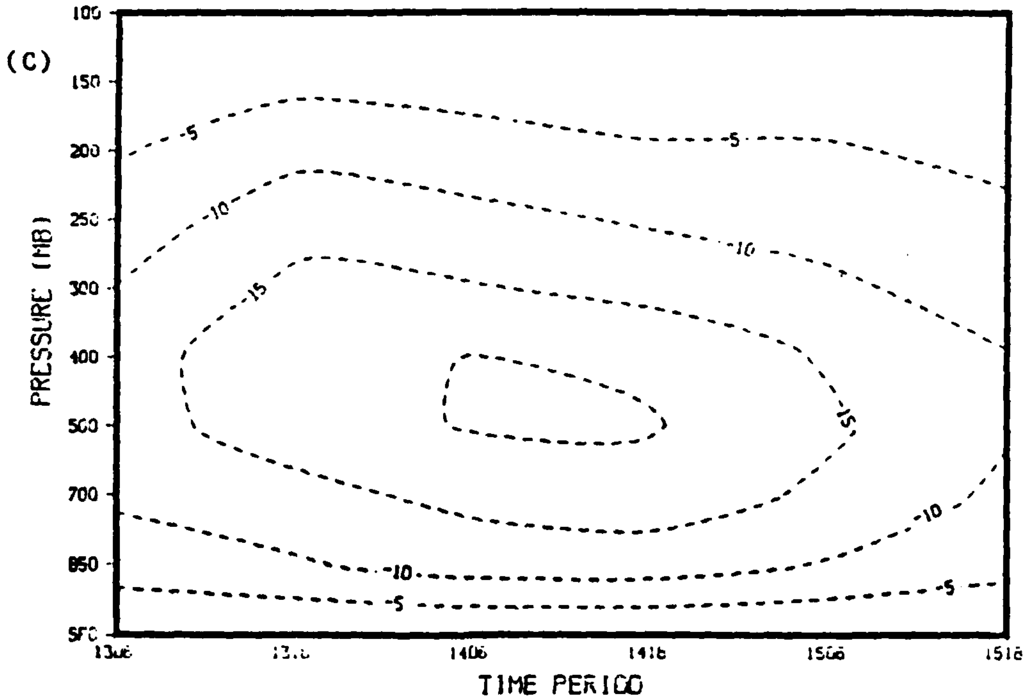


Fig. 2 c.

this term also contains the accumulated computational errors. The maximum heating rate (25° C/day) appeared around 700 mb at 18 GMT 13 January in the predictions and around 600 mb at 18 GMT 14 January in the EMCWF analyses. In both the analysis and the prediction, a weak cooling region occurred near the surface at the time of maximum heating. This low-level cooling may be due to the evaporation of large-scale precipitation.

Column-averaged values of the individual terms in the heat budget are shown in Fig. 5. For the predicted cyclone, the heating rate has a maximum value of 9.8°C/day during the explosive deepening phase at 18 GMT 13 January. The horizontal temperature advection is about two thirds of the heating term and has a similar phase. For the analyzed cyclone, the column-averaged heating rate has two peaks and the maximum value appears during the most rapidly deepening phase (18 GMT 14 January). During this period the

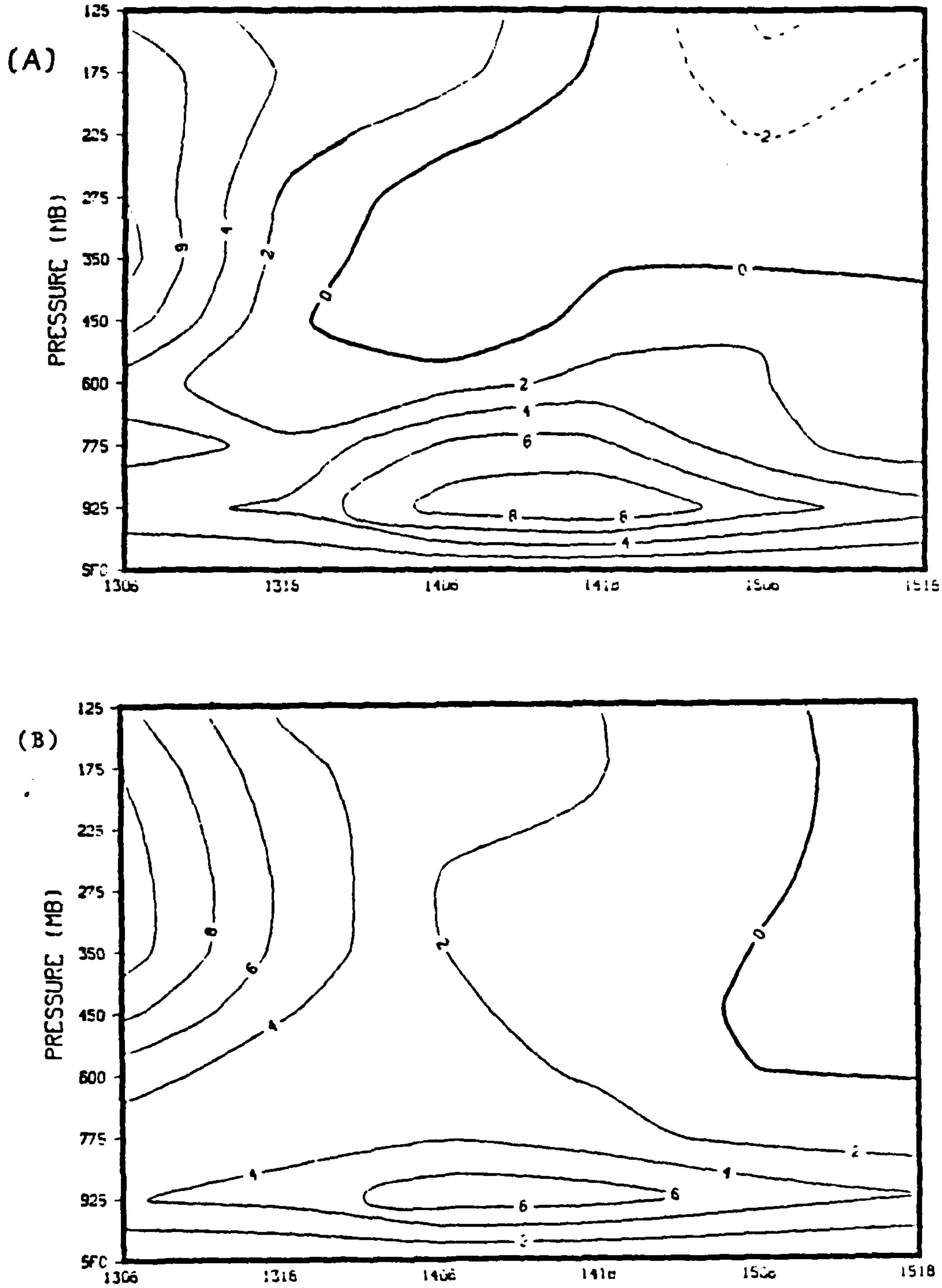


Fig. 3 As in Fig. 2, except for area-averaged lateral vorticity transport.

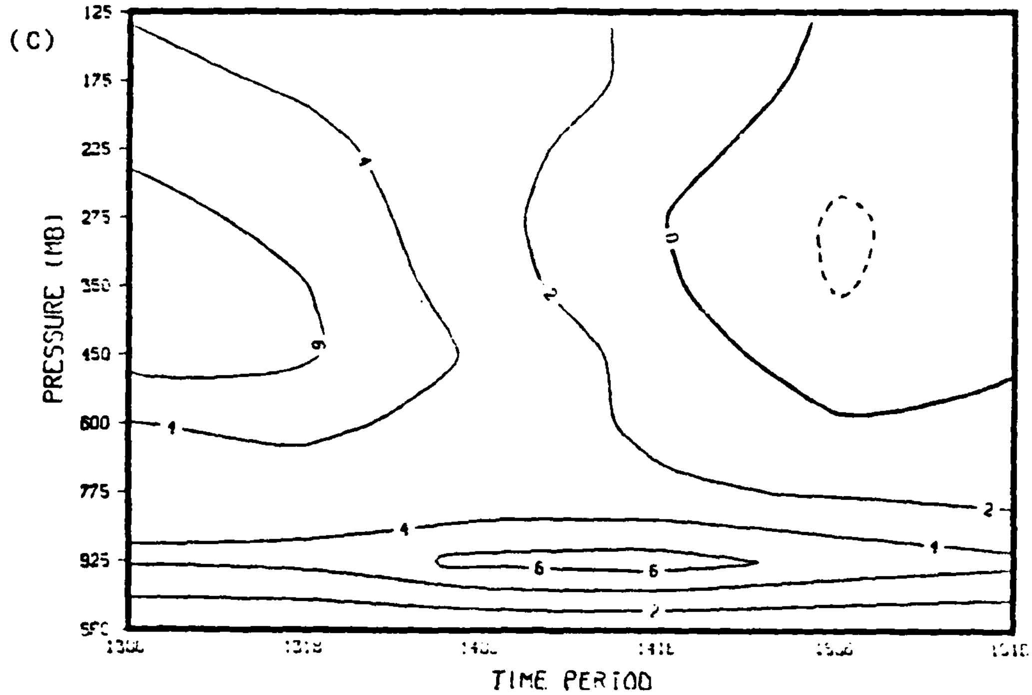
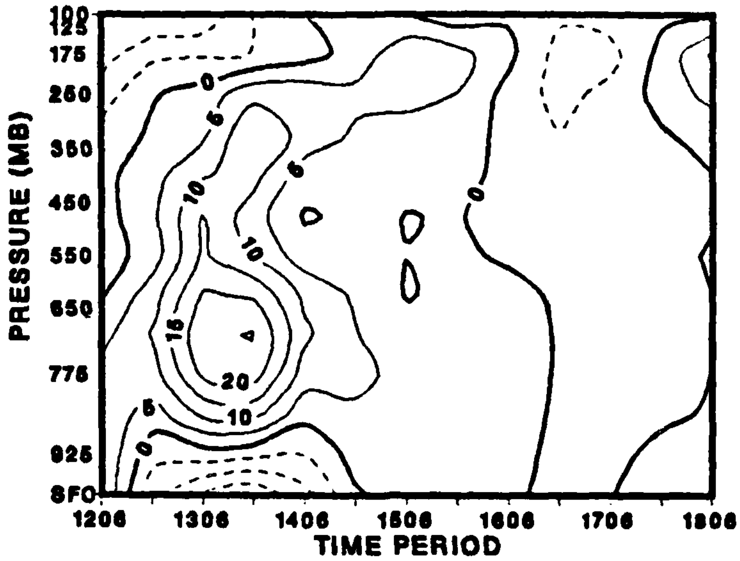


Fig. 3c.

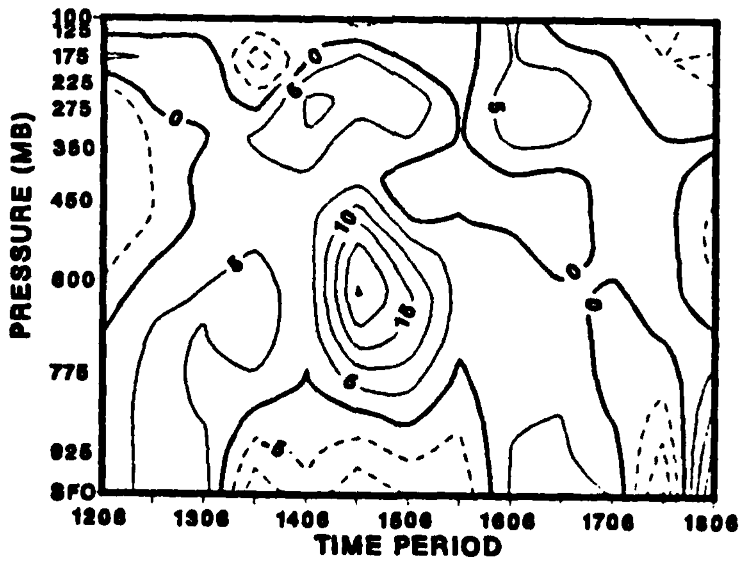
horizontal temperature advection contributes to a cooling tendency.

For both analysis and prediction, the trends in the heating rate are very similar to the trends in sea-level pressure (SLP) decreases (Fig. 6). The similarity in these two trends strongly suggests that the SLP evolution is closely associated with diabatic processes. Consequently, the incorrect prediction of cyclone deepening may be associated with an incorrect phase in the heating rate predicted by the UCLA model.

As an additional validation of the heat budget, the column-averaged heating rate may be compared with the area-averaged total precipitation rate from the forecast model (Fig. 7). The majority of the precipitation predicted around the cyclone was large scale in nature rather than convective. The maximum precipitation rate is equivalent to a column-averaged heating rate of



(a)



(b)

Fig. 4 Diagnosed diabatic heating rate (°C/day) of the (a) Predicted cyclone (b) Analyzed cyclone. The radius of budget volume is 4° latitude.

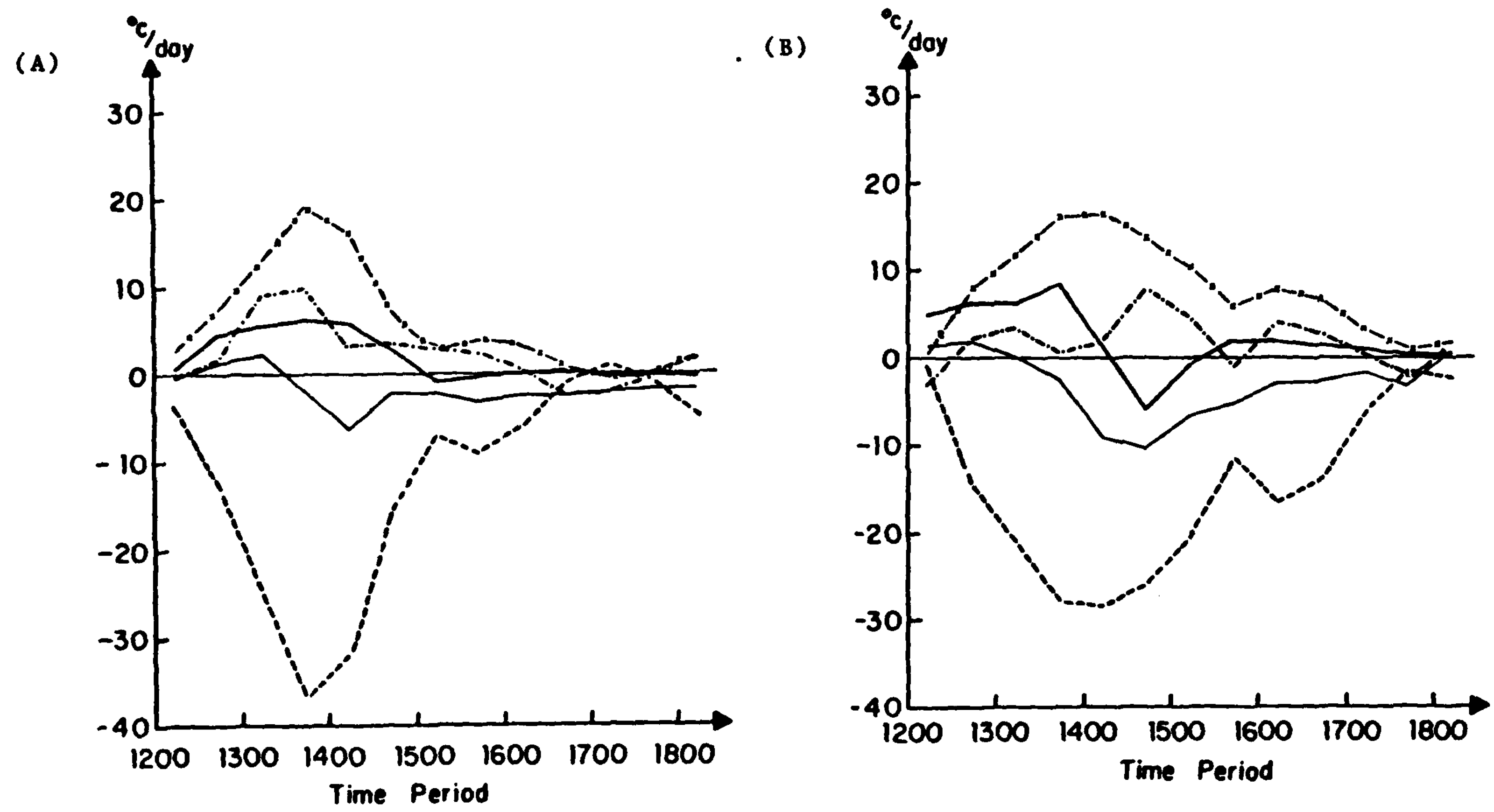


Fig. 5 Column-averaged budget results of the (a) predicted (b) analyzed cyclones: temperature tendency (solid thin), horizontal temperature advection (solid heavy), vertical temperature advection (cross), diabatic heating (dotted) and $\frac{\omega\alpha}{C_p}$ (dashed) terms.

about 10°C/day, which matches rather well the diagnosed heating rate. Thus, latent heat release is the dominant diabatic process.

To summarize, the heat budgets from FGGE analyses and UCLA predictions seem to be physically consistent. In this explosive cyclogenesis case, there is a good correlation between the central sea-level pressure decreases and the latent heat release.

c. Semi-prognostic estimates of diabatic processes. Detailed records of the separate contributions to the total heating rate have not been available during the data assimilation cycles for the FGGE periods. Thus, a semi-prognostic technique for inferring the separate contributions was developed (Winninghoff and Elsberry, 1983) and tested (Bosse, 1984). An iterative procedure is used to diagnose the subgrid processes that would be predicted by the NOGAPS planetary boundary layer and latent heat release parameterizations if the analyzed fields represented one step in a prognosis.

Bosse (1984) applied the semi-prognostic technique to the same western North Pacific case described above. The inferred total diabatic tendency at each analysis time is shown in Fig. 8. Although the maximum heating rate of 30°C/day is similar in magnitude and timing to the values from the large-scale heat budget in Fig. 5, the vertical distributions are quite different. The maximum heating from the semi-prognosis technique is in the lowest layer, where there is cooling diagnosed from the large-scale budget. Bosse (1984) showed that the semi-prognostic technique led to excessive low-level heating and precipitation estimates as the cold air streamed over the warm western Pacific. At 18 GMT 13 January (time of maximum deepening), the heating rate inferred from the semi-prognostic technique was associated with convective heating. Recall that large-scale precipitation was the dominant process in the UCLA model prediction at this time (Fig. 7).

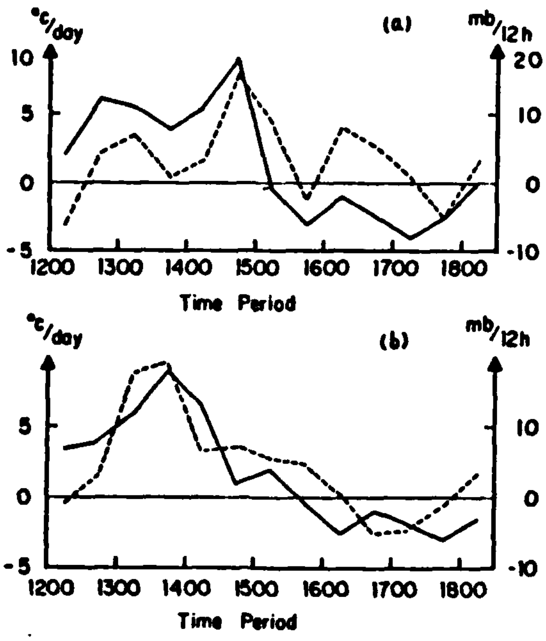


Fig. 6 Central sea-level pressure decreases (solid) and diabatic heating rate (dashed) for (a) ECMWF analyses (b) UCLA forecasts.

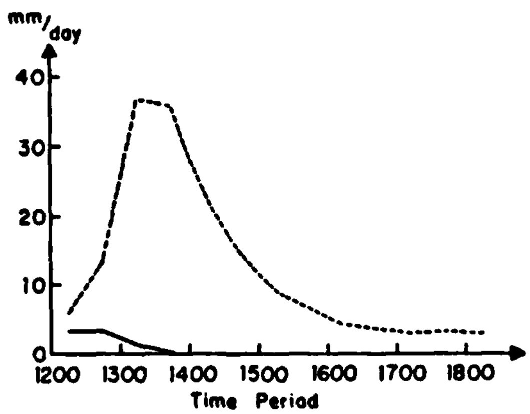


Fig. 7 Area-averaged forecast precipitation rate (mm/day). Dashed line is for large-scale precipitation and solid line is for deep cumulus convection.

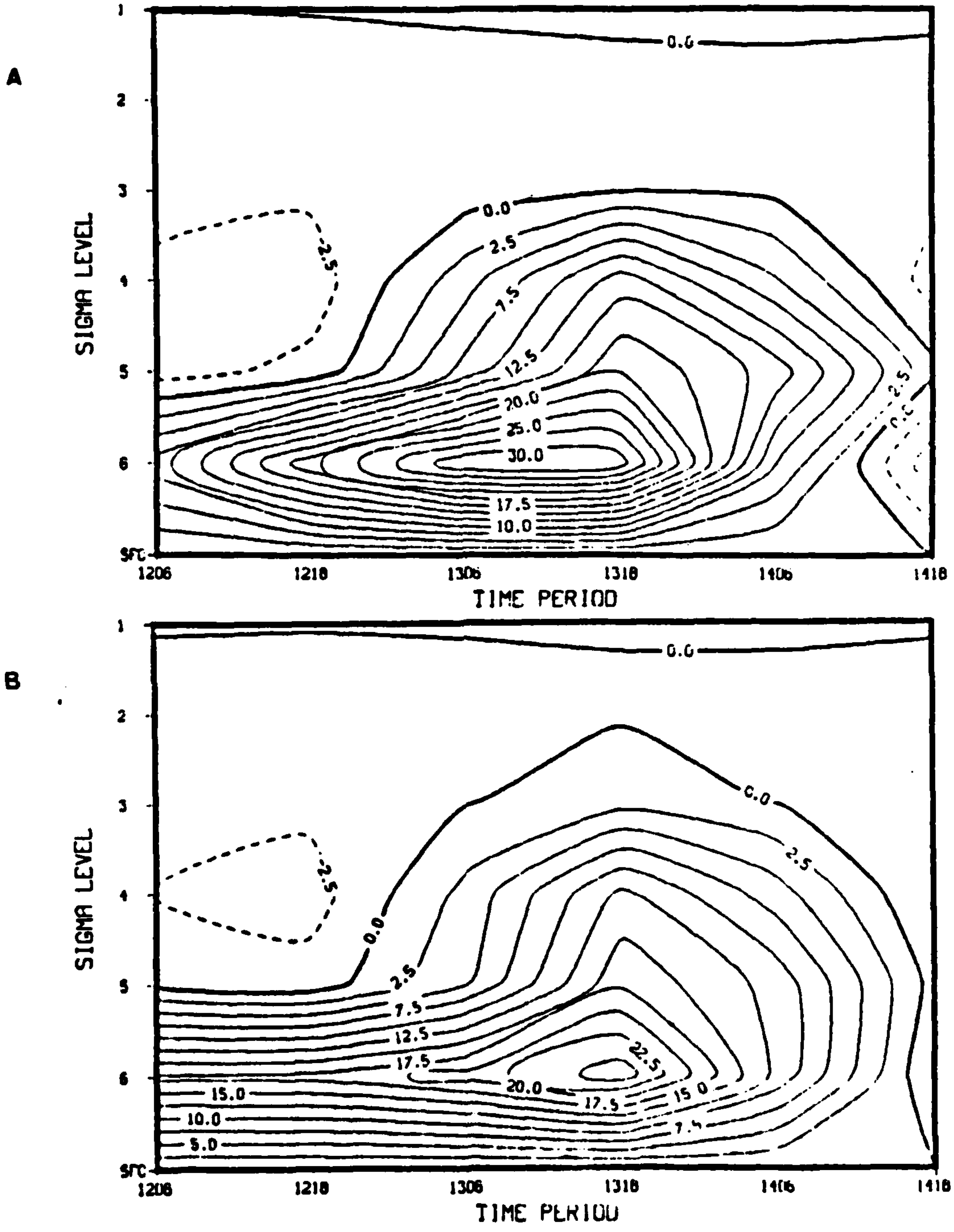


Fig. 8. Contribution of diabatic processes in NOGAPS to time tendency of temperature (°K/day), with negative tendencies dashed, for (a) 6° lat. and (b) 10° lat. radius. Period 1206 refers to the average over the period 00-12 GMT 12 January 1979.

One of the outputs of the semi-prognostic technique is the vertical distribution of radiative heating and long-wave cooling. Large cooling rates are inferred at the top of the stratus layer and extend into the mid-troposphere (Bosse, 1984, p. 149). The long-wave cooling values are roughly consistent with estimates by Professor K.-N. Liou (personal communication, March 1985). However, the amount of stratus inferred by the semi-prognostic technique may be too large. This is consistent with the excessive sensible and latent heat fluxes from the ocean in the NOGAPS parameterizations during cold outbreaks (Dr. T. Rosmond, personal communication). Bosse (1984) also compared the inferred cloud amounts and types with the Defense Meteorological Satellite Program visual and infrared imagery. Convection in the vicinity of the storm center and frontal regions appear to be well predicted by the model parameterization. However, there is a shift to the west of the verifying positions at several of the evaluation times.

The semi-prognostic technique was also tested in cases of post-frontal convection along the west coast of the United States (Winninghoff and Elsberry, 1983). Five cases during the first Special Observing Period of FGGE were selected for quantitative study using ECMWF Level III-B analyses. The post-frontal convective clusters are normally found within or in advance of the 700 mb thermal trough and in regions of minimum 850-700 mb static stability. That is, the column is being destabilized by cold advection aloft while the surface layers are being warmed via southward translation over higher sea-surface temperatures. One of the most interesting aspects was that the inferred convective latent heat release from the semi-prognostic technique provided a relatively good indication of the areas with convection, although the intensity of the convection appears too strong. Diagnostic use of the NOGAPS parameterization as in this study only suggests the potential for prediction

of the post-frontal convective areas. Correct prediction also involves the proper vertical flux convergences of heat, moisture and momentum within the column.

The potential benefits of a semi-prognostic technique in terms of vertical and horizontal distributions of the heating rate from analyzed fields would seem to justify further experimentation and testing. Although the results would obviously be model-dependent, we have so little knowledge of the heating distributions in maritime cyclones that such estimates would at least provide a basis for designing future field experiments.

5. Summary

The objective of this research has been to better understand the development, maturation and decay of maritime extratropical cyclones using a combined observational and numerical modeling approach. This research contributes to the GARP objectives of improving models for weather prediction and increasing predictability over oceanic regions.

One of the basic results of this study has been a demonstration that the FGGE data are useful for the study of maritime extratropical cyclones. This is in contrast to the situation in tropical regions, where presently available analyses have been shown to be inadequate for diagnostic studies. Careful synoptic comparisons and satellite interpretations have been made to demonstrate consistency in the veracity of the FGGE analyses in the region of these extratropical cyclones. The budget studies are another form of validation of these FGGE analyses. Although there are some periods in which the analyses are suspect, the overall conclusion is that the enhanced data sources and improved data assimilation techniques did provide adequate analyses of maritime extratropical cyclones during FGGE.

One of the primary scientific conclusions of the study is the documentation of the role of jet streaks and low-level static stability in the rapid deepening of maritime cyclones. In each of the three cases studied, the rapid deepening phase coincided with propagation of an upper-level jet streak into the region. Small values of static stability in the low troposphere are found within the storm environment in each of the three cases. Given the availability of moisture in the marine environment, the low static stability contributes to enhanced convective overturning and to the smaller horizontal scales of the maritime cyclones.

The quasi-Lagrangian budget studies based on FGGE data provide

quantitative descriptions of the three extratropical cyclone cases. Vertical circulation trends in the mass budget are consistent with the sea-level pressure evolution in each case. Inward transport of vorticity due to the jet streak coincides with the rapid development phase. The processes which lead to the spin-up of these maritime cyclones appear to be consistent with earlier studies of continental cyclones.

Similar diagnostic studies with model-generated data have been done as a complement to the observational studies. The numerically-simulated cyclone studies have the advantage of complete and accurate data. The three-hourly time resolution provided in the model data contrasts with our experience that only the 00 and 12 GMT FGGE analyses were sufficiently accurate for budget studies. The excellent resolution in the model data allowed documentation of the complete evolution of two small maritime cyclones. One of these circulations developed from a pre-existing disturbance and the other was induced by a mid-tropospheric short wave. Similar evolutions have been proposed for real-world cases, but such differences have been difficult to establish over the data-sparse polar oceans.

The model-generated case studies also involved cyclogenesis under straight upper-level flow. Using the same diagnostic tools, the residuals in the budgets were acceptably small. These studies demonstrate that similar physical mechanisms are involved in the simulated storms as were found in the observational studies. Although the arrangement was slightly different, the rapid deepening phase occurred in conjunction with an upper-level jet streak. Low-level static stability changes in the model also play a similar role as suggested in the observational studies. We thus have additional confidence in the qualitative and quantitative results of the FGGE-based studies. These model-generated cases also suggest that new data sources will be required to

detect the jet streaks and low-level static stability conditions that seem to be necessary for accurate predictions.

Finally, we have examined two sets of numerical model predictions based on FGGE analyses. Most of our studies have focused on a single case of explosive cyclogenesis in the western North Pacific. Both the GLAS and UCLA models predicted the most rapid deepening phase too early and resulted in excessively low sea-level pressures. This contrasts with earlier studies of explosive cyclogenesis for which the operational numerical weather prediction models under-predicted the development.

For this single case, the NOSAT analysis (excluding all forms of satellite data) resulted in a more accurate prediction of the track and sea-level pressure evolution. The most important factor was an incorrect specification of the satellite cloud-drift winds in the region of the jet stream. Low-level static stability differences between the model and the analyses indicate that the representation of the physical processes is also important.

Heat budget studies were used to determine the vertical distribution of heating in the model in comparison to that deduced from the FGGE analyses. These studies indicate very large heating rates in this maritime cyclone compared to earlier studies of continental cyclones. The diabatic processes are of similar magnitude as the horizontal temperature advection. Furthermore, the sea-level pressure evolution seems to be highly correlated with the magnitude of the heating rate.

A semi-prognostic technique was developed for inferring the diabatic process, including the surface fluxes, from analyses of the wind, temperature and humidity fields. This technique would allow extensive studies of the diabatic processes from the archived FGGE analyses. Only limited comparisons

have been made with the satellite imagery in the western North Pacific cyclogenesis event and for five cases of post-frontal convective areas off the west coast of the U.S.A. An intercomparison study with numerical model output showed similar maximum heating rates as deduced from the semi-prognostic technique. However, the semi-prognostic approach indicated the heating was due to convective heat release, whereas the heating in the model was actually associated with large-scale precipitation.

We conclude that the FGGE analyses provide for the first time a consistent data set for study of extratropical cyclones over the ocean. Rapid intensification of these cyclones in straight flow aloft has been documented from observations and models when a jet streak is present. Small static stability in the lower troposphere is shown to be an integral feature of the maritime cyclogenesis cases. Numerical model studies proved to be a useful complement to the observational studies. For reasons that are not completely clear, the numerical predictions of rapid cyclogenesis in this single FGGE case are much better than previous operational model predictions.

Further studies of maritime cyclones with the existing and future improved FGGE analyses seem to be justified. Such studies are necessary to provide validation of the conclusions of this limited study. There needs to be many more evaluations of the impact of satellite data on predictions over the ocean. Further intercomparisons of models and analyses are desirable to document the accuracy of the predictions from FGGE data, and to establish that the correct physical mechanisms are involved. We will then have reached our goals of improved understanding and an ability to predict maritime extratropical cyclones.

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